Amici's Reflectors and Refractors

Pasquale Tucci[1]

1. Introduction

In 1811, when he was just 25 years old, Amici sent to the astronomers of the Brera astronomical Observatory in Milan two reflecting telescopes requesting that their quality be tested. The telescopes were the largest existing in Italy at that time; one telescope had been built for Pietro Moscati's small observatory; the other was a gift to Brera. The Brera astronomers tested one of them and praised Amici's skill and the performance of his product. They were so enthusiastic that they asked the government to give Amici a commission for a much larger telescope. (For more details see A. Mandrino et al. , 1989.)

For more than 15 years Amici continued to built reflecting telescopes because he was convinced that their performances were better than those of the refractors. But between 1825–1827 he started to devise and to manufacture achromatic lenses for refractors.

In this communication I'll try, on the basis of published documentation, to reconstruct the way in which Amici decided to built refractors rather than reflectors.

2. Reflectors

The first optical instruments made by Amici were the reflecting telescopes, which he used to perform his first researches.

[1]Istituto di Fisica Generale Applicata, Univ. degli Studi di Milano

As for glass manufacture, the different makers used various kinds of alloys. In his memoir "Lettre sur les observations des satellites de Jupiter en plein jour", (1825), Amici described his mirrors made by a "friable and not very solid alloy". This kind of alloy was judged unsuitable for the manufacture of large glasses like those of W. Herschel, which were made of a "more solid" alloy but whose reflection factor was much lower.

Since each mirror-maker used a different kind of alloy in the manufacture of the mirrors for telescopes, their reflection factor being different, Amici thought it would be useful to make comparative measurements of the luminosity of this telescopes and refractors.

At that time, especially in Germany, the refractive index started to be almost definitely as an exact standard parameter of the lenses; therefore Amici, by comparing the luminosity of one of his telescopes with that of a refractor, was able to obtain exact relative measurements. In his memoir on the satellites of Jupiter just above mentioned, he described the method he had used to get these measurements which allowed him to establish the ratio between the loss of light in the reflection and in the refraction. Amici recalls that Herschel had described similar experiences in the *Philosophocal Transactions* published in 1800. Clearly the luminosity of the mirror of a reflector was less, compared with that of a refractor having the same aperture. The magnifying power, the eye-pieces and the focal lenght of the objectives being equal, Amici determined a value of 3/4 of the ratio between the refractor and the reflector luminosity. This value was simply obtained as the ratio of the diaphragms diameters placed on the objectives of the two instruments in order to obtain the same luminosity in the respective eye-pieces. Therefore the diaphragms were necessary for limiting suitably the luminous flux of his two instruments.

In order to determine the exact measure of the luminosity in each of the two instruments, Amici used a parallelepiped 3 inches long, which was ontained by joining two opposit prisms, one having a white glass, the other a dark one. Therefore the double prism had a varying transparency along its lenght and it was usually used to obtain a continous variability of the luminosity of the Sun images. Amici used it to measure the luminosity of a star when its image disappeared completely in the eye-piece. He could obtain this result thanks to a given position of the parallelepiped, sliding on a graduated guide and transversal to the eye-piece field. Amici could detect the same position of the parallelepiped on the graduated scale at the moment when the image would disappear completely on both instruments, when each of their objectives was properly diaphragmed. By these operations he had obtained that the luminosity of one of his refractors was 25% brighter than that of a reflector of his. He judged the value 3/4 the right one for all his reflectors and refractors production, in the approximation of the thin lenses, namely in the assumption that the luminosity was not further fated by a not proportional increase of the glasses thickness of the larger achromatic lenses.

In spite of the higher efficiency of the achromatic lenses Amici knew that it was practically impossible to make refracting objectives whose luminosity could exceed that of the reflectors. These, because of the advanced technique of that time, could be made in big dimensions and therefore they exceeded the efficiency of the refractors. Amici calculated that an achromatic refractor, having the same luminosity as Herschel's largest reflectors, should have had a 40 inches diameter: in his opinion "one could not even hope" to make such an objective. He had obtained the measure of this diameter by using the value 7/10 measured by Herschel, tallying his 3/4 value. Amici knew also that Herschel had obtained 5/6 by eliminating the small mirror of the Newtonian.

After all, in 1825 Amici had a preference for the reflecting telescopes. This opinion was due essentially to the fact that the reflectors, having a larger number of magnifications, had, in consequence, a better "clarity and neatness of the images", a shorther lenght of the tube and thereby they were much easier to handle. He judged the refracting telescopes advantageous and useful for many purposes. In fact, as I have already mentioned, they gave more brightness, in spite of their shorter diameter, they were easier to be equipped with a micrometer and, being able to stand the wear of time, they allowed to make, over the years, comparison between the same observations.

But, above all, being the centering of their objective permanently steady, their use was immediate. Amici recalled that this very characteristic was, for some astronomers, the determining factor for choosing either a reflector or a refractor. In fact Amici himself emphasized the fundamental importance of this feature because the use of a reflectors required a careful and gauged centering of the objective position.

From these considerations, drawn from his memoir of 1825, it appears that Amici, up to about that date, had a preference for the construction of reflectors, most of all because they were more suitable for the most significant astronomical observations. On the other and it does not appear that before 1825 he had made achromatic lenses of high quality, with alternative performances to his reflectors. Actually he started to be actively interested in achromatic lenses and begun to make them between 1825 and 1827.

Certainly the first techniques used for the manufacture of the mirrors for telescopes, which had been set-up since 1809, became very quickly up to a production of great importance. As a matter of fact Amici succeeded very quickly in asserting his superiority in Italy for his production of telescopes. In 1811 Amici could already announce to the Minister of Interior then in charge, count Pietro Moscati, who was entrusted with the Department of Education, that his main purpose was the manufacture of reflecting telescopes whose perfection could be compared with that reached in other countries, where there was already a tradition in this field. In fact in Italy there was not practically any high quality production of these instruments. Amici's aim was certainly anything but vain, actually in the course of the same year he received the first appreciation by the Italian Government for his work as optician.

On the August 1811 the 'Istituto Italiano' awarded him the first prize for the manufacture of a telescope of prize for the manufacture of a Cassagrainian telescope, equal to that of Herschel.

The fame he won in Italy in 1811 was also a consequence of this considerable and efficient production he had shown, in that time, as a telescope maker. In fact he was able to produce in few months first rate telescopes, with high magnifying power. As above mentioned the production of a telescope was fundamentally conditioned by the objective-glass manufacture: in fact the wider its diameter and the longer its focal lenght was, the greater was the difficulty of its manufacture. One of his first telescopes he made, had a 6 inches wide glass, 2 lines aperture and a remarkable 7 1/2 feet focal length.

Amici had already made a deep research work on the possibility of increasing the magnifying power of the telescopes. In his memoir about Jupiter's Satellites in full daylight he wrote that he had discovered a limit to the increasing of the magnifying power, due to the light diffraction. For some time he had noticed that while observing the fixed stars at different magnifications of the telescope, when he split the image by parting the two semilenses of the divided object glass micrometer, two oval shaped images would appear. The shortest diameter of these images was the same as that of the apparent diameter before the splitting. By centering properly the reflector, he obtained two images, having an oval shape as well, of which he could measure the apparent diameter. This was possible because the oval shape of the images, that is their longest diameter, appeared perpendicular to the cut of the two two semilenses of the divided object glass micrometer.

The deformation of the images, due to large magnifications, appeared only when observing the stars, while it would not occur when observing, for instance, Jupiter's satellites: and that would occur although their apparent diameters were shorter than those of some fixed stars. From these considerations Amici would deduce the possibility of discriminating quickly a planet from a star. This possibility depended on the ability of discriminating a true disk from a false one, that is a disk made up by images of diffraction.

Herschel also, in the *Philosophical Transactions* of 1805 had published a method which allowed to discriminate a false disk from a real one, provided that the diameter of the latter was 1/4 second larger. Herschel had noticed that the rays coming from the central areas of the reflecting mirror tended to widen the false disks, whereas the rays near the edge of the mirror tended to make them smaller. Amici had checked that the oval shape could not depend on the aberration of the light on the mirror, that is on the spherical aberration. In this case, in fact, he would have expected the lengthening towards the diameter of the semicircle. With the micrometer mounted on the telescope he would have expected the lengthening towards the cut of the two semilenses of the micrometer. Amici had also noticed that by bringing nearer or moving the eye-piece away from the mirror of the telescope, starting from a position of clear vision, a very narrow and brighter band of light would appear on the edge of the star image.

Amici deduced that all the phenomena observed had the same origin. He came to the conclusion that the only cause which could produce these effects was the inflexion of the light on the corners of a diaphragm walls: very probably the diaphragm walls were the edges of the small mirror and of its arm and the edge of the embedment of the large mirror. Amici concluded that the inclination of the light was the only obstacle to the manufacture of reflectors having a boundless magnifying power.

A proof of the perfection achieved by his reflecting (Newtonian) telescopes is given by his observations of Jupiter's satellites made at full daylight. These observations, because of their inherent difficulty, even if made in favorable meteorological situations, were unique in the catalogues of the astronomical observations; they had won the attention of many astronomers. Amici had measured Jupiter's and its satellites apparent diameters by using one of his divided object glass micrometer and mounted on a telescope equipped with lenses which allowed hundreds of magnification power. The first observation he made was carried out on the 1st, 2nd and 3rd February 1822 and he announced them in his memoir about the prismatic micrometers which appeared in the Zach Correpsondence in 1823. In this occasion Amici had used a Newtonian telescope of 11 inches aperture and eight feet focal distance and had not made micrometric observations. On request by the astronomer Zach, he made other observations, by using a telescope of the same dimensions as the one just mentioned, equipped with a 'intermediate' micrometer. He gave a description of it in the above mentioned memoir on Jupiter's satellites in full daylight. With these latest observations he measured Jupiter's apparent diameters and those of its satellites. He then cecked, by means of simple computations, the measurements he had obtained which appeared, finally, very reliable. This result was certainly due also to the good characteristics of the telescope he had used. In the first instance one can hold for certain that such a telescope was fully satisfactory as for requisites of the centering of the optical systems and their relatively high reflectivity as well as for the good correction of the aberrations.

Moreover, supposing that an astronomer wanted to repeat his daytime observations with an achromatic telescope, Amici, in his latest memoir, had also established the dimensions of an achromatic telescope which would allow to detect in the same conditions and with the same clarity, the satellites that he had detected with the 11 inches and eight feet Newtonian telescope. The diameter of such an objective was nearly the same length as that of the largest achromatic lenses which were made at that time. Therefore Amici noticed that the 7 1/4 achromatic telescope of the Observatory of Naples had a lesser luminous efficiency than his telescope. The achromatic telescope at Dorpat, which was about 9 inches, that is 241mm, was on the contrary brighter. It had been made by Fraunhofer and it was the largest achromatic telescope in those days. Actually Amici doubted that it could be better than his. The astronomer from Dorpat had announced, in fact, the observation of the double star 3 Canis Minoris, that is Herschel Prima 23, but he had not detected another little star 41" South which Amici, on the contrary, had been able to spot with his telescope. Moreover he had been able to measure directly the diameter, from center to center, of the two nearest stars, obtaining 1".25. He added that the double star having the smallest apparent diameter he could detect with a telescope provided with a micrometer, was ∞ Leonis whose measurement was 0".5. In a letter to J. Herschel, dated March 16th 1826, he described the efficiency of his telescope of 8 feet focal point and whose 11 inches aperture was identical to that of the well-known refracting telescope at Dorpat. Actually they both had detected in the same way 16 stars near the star σ Orionis. From these considerations it appears that Amici had first rate astronomical telescopes on a European scale.

The objective evidence of the good characteristics of Amici's reflectors is given by some modern measurements of the optical characteristics of a large mirror he made; except for few oxidized spots, it has withstood in enough good conditions till now, so that it can be examined. At the Istituto Nazionale di Ottica at Arcetri, near Florence, it is still preserved, in a frame of 1925, one of Amici's spherical concave mirror of 300mm aperture and 12m bending radius, made of special steel. During the commemoration of Amici's death centenary, celebrated at the University of Modena and published in the magazine *La Ricerca Scientifica*, Ronchi reported that he had tested this mirror in 1922. It had turned out to be optically imperfect because of a slight deformation towards its edge. But this slight imperfection, Ronchi, explained, could be a consequence of the specular surfaces tolerances which are 4 times inferior to those of the refracting surfaces; the latter are lower than one fraction of the wave-length of the mean optical radiation, that is they are of the order of one tenth of a micron. Therefore the mirror tolerance is less than a half tenth of micron. To sum up, Amici had found out some manufacturing processes for mirrors surfaces which would be excellent for lenses. Ronchi concluded that the result was anyhow extraordinary even though imperfect.

Amici modified his telescopes in order to adapt them to the most various requisites needed for the different observations of the Sun, of the comets, of the double stars, etc.. At the Observatory of Florence, for example, Amici had used, among other things, one of his particular reflecting telescopes. Here he used also an 8 feet focus and 11 inches diameter reflecting telescope, an instrument which was then considered, with those of Herschel, the one giving the best performances absolutely.

3. Refractors

Between 1825 an 1827 he started actively the devising and the manufacture of achromatic telescopes. The confirmation of the construction of these achromatic telescopes is given by a letter of von Biella's who, in March 1827, after a journey he had taken to Modena, wrote in the *Astronomische Nachrichten* that, among other things, he had seen many achromatic telescopes in Amici's workshop. Besides he had seen the prototype of a telescope for a transit instrument, of 5 feet focus and 4 inches aperture. Von Biella said also that, for the lenses, in particular those of flint-glass, Amici used to get the glass from Guinand in Neuchâtel, the famous Swiss chemist who had invented the flint-glass manufacturing process.

At that time the greatest manifacture difficulty of an achromatic telescope equipped with high magnifying power, lied essentially in the devising and, above all, in the building of the lenses, in particular those having a very large diameter. An objective was usually made gluing together a crown-glass and a flint-glass lens; the larger was the cube of its diameter, the greater was the difficulty in making the objective.

Moreover the manufacture of good achromatic objectives required a wide availability of kinds of good quality glass, made under a systematic control of their refractor factor, homogeneous enough and without any impurity, that is without striations or veinings. This variety of glass was not avalilable for Amici in Italy. The manufacture of this kind of glass exixted instead in Paris, in Münich and in London, but it did not exist at all in Italy. In his memoir about a new reflection sector he reported about the difficulties he had met in getting the right glass for the prismatic refractors of this instrument: in the end, exceptionally and only for once, he had been able to get it from Fraunhofer.

For this reason he even gave up the plane he had proposed to himself, to produce on a wide scale sectors which, in the prototypes, had been judged a useful instrument for the celestial geodesy.

Again in his memoir of 1836 about the reflection instruments for measuring the angles, he narrated at length the difficulties he had met to find good quality glass. In 1837, having been invited to attend the decennial competition for the manufacturing arts by the *Accademia delle Belle Arti* in Florence, Amici urged the establishment, in Italy, of manufactures which the progress of optics had introduced in other countries. These manufacturing factories produced flint-glass of great purity and transparency for achromatic objectives of more and more perfected and of bigger dimensions. Anyhow his urge turned out to be certainly vain, at least as for his purposes. In fact, in 1848 he could obtain, with a certain difficulty and again from Guinand, the flint-glass and crown-glass for the construction of that instrument which will be his largest achromatic objective; indeed he had to postpone to a year later the final making of this objective, waiting for a new crown-glass disk.

In 1840 he started the construction of an achromatic objective which will be his largest one, second only to that of Fraunhofer. In fact on the 29th July a case arrived to Florence, weighing 75kg and containing some flint-glass and crown-glass disks that Amici had ordered to Guinand. On August 5th 1840 a bill of 2766 francs was issued in Lerebours's favour, an optician of the Navy Observatory who appeared to have collected Guinand's production of glasses. In September 1841, at the third meeting of the Italian Scientists, Amici produced his objective: at the end of its construction it was 285mm in diameter and 533cm in focal length. This instrument had been made in the workshop of the Museum of Physics in Florence and had been finished by the 'artist' Toussain, in accordance with the method devised by Amici to work glasses and clean them. The execution of both the objective and the eye-piece could be considered, in Amici's opinion, truly exact being accurate enough the spherical aberration. But the crown-glass showed 7 considerable groups of veins, therefore as soon as Guinand would make available another crown-glass disk of better quality, Amici would make the lenses again to make perfect a huge instrument. The following year he received a new disk and on the 25th July 1842 a bill of 100 francs was issued in Lerebours's favour, to be cashed in Paris. This small sum was to pay off the crown-glass for which a price had been previously paid with a discount equal to the value of the faulty lens. The latter was intended to be sent back to the workshop, but it remained in the Museum of Physics in Florence instead.

Probably trying to outdo himself or to be better than Fraunhofer, in 1844 he bought two more 11 inches disks of flint-glass and crown-glass. He also reached an agreement with Guinand for the purchase of two more 15 inches disks and he took interest in some disks of 20 inches. These could be suitable for the construction of a huge telescope that, in Amici's opinion, could hardly be built in Paris.

All these considerations show that Amici was interested in making himself other instruments. It is not known if the negotiation with Guinand concerning the 15 inches disks was carried out. The two disks of 11 inches, that is 28cm, on the contrary, were transformed into the two elements of his second major objective, whose focal length was 318cm and whose diameter 23.8cm. It is very likely that this small aperture was a consequence of an optical defect in the edge of the disks which surely were not of the best quality: actually, a minute inspection of these disks shows many little air bubbles strewn everywhere. This second objective mounted upon a rather simple wooden stand, was Amici's very property and he used it at home for his sporadic astronomical observations.

His two greatest objectives, described above, were tested by

Ronchi in 1922. In his report about Amici's work where he related the results of these tests, Ronchi, first of all, pointed out the remarkable values of the tolerances needed for the construction of these lenses and the great difficulty in making them. These tolerances had to be inferior to a fraction of the mean wave-length of the optical radiation, that is they had to be of the magnitude order of the tenth of a micron. The difficulties in manufacturing these lenses, besides, would grow with the cube of the diameter itself. Ronchi underlined that these technological notions were not known in Amici's days.

Besides, even before the beginning of the 20th century, the optics technique was still approximative. They would work at random, by making an attempt after another without knowing if the glass was homogeneous enough, if the surfaces were near enough to the planned ones or even if the glass quality was the right one. In the light of these considerations Ronchi concluded that the largest objective was exceptionally corresponding to the estimated tolerances, but not quite so was the second one, also because of the little air bubbles, due to the faulty glass melting.

After Amici's death, his two largest objectives were used in Italy as lenses of first rate telescopes: the largest one was used for the equatorial mounting in Arcetri up to 1926. The equatorial mounting of the telescope installed by Amici in the Museum Observatory must have been not very satisfactory and the astronomical observations were difficult and tiring. Therefore in 1864, after his death, the Parliament appropriated a sum of 44.000 lire for a new equatorial mounting which Donati and Tempel used successfully, but still with an imperfect mounting. In 1872 these telescopes were moved to the new observatory, built on the hill of Arcetri, and opened on the 27th October of the same year. In that occasion Tempel emphasized again the precarious and imperfect mounting of the two telescopes. On the 16th March 1889 Tempel died and afterwards the observatory was relinquished for 5 years.

In 1894 the new director Antonio Abetti found it in a crumbling condition: the huge equatorial Amici had been removed from its pedestal and placed elsewhere, in order to avoid that the down fall of the obeservatory might cause to it further damage. Abetti then, an engineer and astronomer, provided the telescope with a new mounting, using only the pedestal of the old one. This new mounting had been devised so that it could be equipped with an objective larger than that of Amici in case that it might be got over, but it was not, by the more modern achromatic objectives. Abetti intended to have the equatorial ready at the end of 1894. In 1897 this work was ended. Abetti himself and, later on, his son Giorgio, who succeeded him, used the Amici telescope for more than one forth of a century for micrometric measurements of asteroids, comets, double stars and for studying the solar prominences.

In 1926 the 285mm Amici objective was replaced by a Zeiss of 360mm in diameter and an eye-piece slightly bigger. In 1931 Giorgio Abetti used again Amici telescope as short focus objective for the solar tower. In 1936 the 2 Amici objectives were used in a spectograph for the observations of the total solar eclipse on the 19th June in the Soviet Union; so he did also in 1952. In the early 70's the two objectives were still used for researches, laboratory experiments and for the inspection of optical systems.

Morais's article of 1965, about an objective made by Amici according to Mossotti's theory, expounds the construction by Amici of another special type of achromatic objective. As a matter of fact Amici had made remarkable objectives equipped with 3 glued lenses but whose project was only partially his own. That part of the project he had not devised himself, was the work of a disciple of Mossotti's, Dr. Angelo Forti.

On the 5th September 1852 he produced to the Accademia Valdarnese the results of a project of a 3 glued lenses objective, that he had obtained from a numerical application of the general theory aberration, expounded by his master O. F. Mossotti, professor of celestial mechanics at the University of Pisa.

By using these results which gave only the 4 normalized radius of curvature of the 3 lenses and which, therefore, were incomplete for the construction of an objective, Amici made an objective of 6 inches in aperture and 52 inches in focus with whose characteristics he was very much satisfied. As a consequence of the good result obtained, in 1857 Mossotti published, in the "Annali dell'Università Toscana", his "Nuova Teoria degli Stromenti Ottici". It was a research about the aberrations of the objectives and it gave some analytical expressions which were an abstract of those already known: that is, those about the chromatic longitudinal aberration corrected for two selected radiations, and that of Clairaut. The latter, in 1756-57, had given the analytical expression of the spherical aberration, by publishing it in the *Mémoires de l'Académie des Sciences* of Paris.

Mossotti, as a special application to the astronomy, had studied stigmatism for a monochromatic source, adjusted for infinity, which was not on the optical axis of the lens but near it. This way he could correct also the objective from the sine aberration, whose cancellation conditioned the good quality of the images out of the optical axis. This way the objective was achromatic and aplanatic. His theory was suitable for the microscopes objectives as well. Amici used willingly the results of Mossotti's theory because it was a very general one and gave solution of a kind of aberration never considered before.

On the other hand he could never have obtained such results which were based on an extensive mathematical treatment, in whose formulation he had never taken an interest. Mossotti, on the contrary, had given an elaborated theoretical formulation. He had written 2 equations in order to obtain the chromatic correction and a desired focal curvature equal to one in the calculations.

In conclusion Morais underlines the exceptionality of the triple objective made by Amici, because in those days there were only two possible corrections for the objectives and therefore only two lenses could be used. In fact he recalls the usual objectives: first of all that of Clairaut with two glued lenses, of which Mossotti showed the stigmatism of the images near the optical axis, owing to the right choice of the glasses. Secondly that of Fraunhofer corrected of its spherical aberration at the minimum distance of 40 focal distances and to infinity: the double correction of this objective gave a good aplanatism of the system. Finally that of Gauss, corrected of its spherical aberration for 2 different radiations.

Morais recalls that objectives with 3 glued or not glued lenses were devised as well, only to increase their relative aperture. None of them made up an aplanatic system. It is certain that in those days Amici-Mossotti objective was unsurpassed in its structure: up to now such an objectivee is most valuable.

In a final valuation about the wotk that Amici brought to an end Morais points out Amici's scientific sensibility in perceiving the fertility of the new theory about the aberrations in general and in encouraging Mossotti by a positive valuation, so stimulating him to publish his work.

4. Conclusions

There is no doubt that Amici's astronomical instruments - both reflectors and refractors - were comparable, as to their performances, with those built in other european countries, although Amici had some difficulties to buy glass for his refractors. But the general weakness of industrial structures and the financial difficulties of many institutions involved in scientific and technological researches didn't allow the development of workshops specialized in making scientific instruments. So, when in the second half of the 1800, Italian Governement did a big effort for equipping the astronomical observatories with new instruments, most of them were bought abroad.

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